Manufacturing and characterisation of lasers with wet chemically etched mirrors integrated with a photodetector

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TTE-EEA 540

Period: October 1996- August 1997

Master's thesis for the degree of electrical engineer.

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The faculty of Electrical Engineering of the Eindhoven University of Technology is not responsible for the contents of this report.
Abstract

The wet chemically etched mirror laser (WCEML) is just like any other semiconductor laser an optical waveguide with gain, terminated at both sides by mirrors. These mirrors are obtained by wet chemical etching rather than cleaving. The WCEML is for two reasons an interesting device:
1: the WCEML can be made much shorter than a conventional laser with cleaved mirrors.
2: the WCEML can be monolithically integrated with other devices, like a photodetector.

Within the TUE group Electronic Devices a universal manufacturing process for WCEMLs has been developed, by which devices with lengths varying from 750 \( \mu \text{m} \) down to 7 \( \mu \text{m} \) can be fabricated. To fabricate a GaAs/AlGaAs WCEML, four lithography steps are required:
1: etching the ridges and deposition of the passivation layer
2: evaporation of the p-contact
3: opening windows in the passivation layer for the mirrors
4: wet chemical etching of the mirrors.

After these steps the wafer is polished, after which step the n-contact metallisation is applied. Cleaving of the wafer concludes the process. With this universal process WCEMLs with various layer structures can be processed. After optimising the first two steps of the process GaAs/AlGaAs WCEML's with either two or three quantumwells have been manufactured. Also WCEMLs with a bulk active layer has been fabricated.

The short cavity devices with multiple quantumwell active layers (shorter than 200 \( \mu \text{m} \)) show the phenomenon of multiple wavelength emission. This is explained by the fact that the energy inside the quantumwell is divided in several discrete levels. Shrot WCEMLs with a bulk active layer do not show this behaviour. It occurred that a short WCEML with two quantumwells showed emission at up to five different wavelengths.

Also the monolithic integration of a GaAs/AlGaAs WCEML with a detector is presented. This requires one additional step, done after etching windows in the passivation layer. The additional step results in an etch groove with overcut sidewalls,
of which the one nearest to the detector ridge is used as detector facet. A tilt in the facet is made to avoid unwanted reflections from the detector facet back to the laser. The detector photocurrent has shown an almost linear dependence on the laser optical output. The detector has a sensitivity of about 12 nA/mW. The spectra of the integrated lasers with detectors have shown no change in comparison to separate WCEMLs made in the same material system, indicating that the laser is not suffering from unwanted reflections.
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Chapter 1

Introduction

In 1962 the first semiconductor laser was presented. In 1970 the first semiconductor laser operating at room temperature was shown to the world. Since then the semiconductor laser has experienced enormous attention. Today, it has found many applications such as for glass fiber communications, optical recording and barcode scanning.

A laser can be regarded as being an optical waveguide with gain terminated at both sides by a mirror. The light inside the waveguide is amplified rather than attenuated. Ideally the lightbeam is monochromatic and coherent.

Most semiconductor lasers are of the edge emitting type, i.e. the light beam emitted is parallel to the semiconductor surface. The mirrors are in fact cleavage planes, which are very smooth. These devices are easy to manufacture. One drawback is the impossibility to integrate the conventional edge emitting laser with other devices, like transistors or photodetectors, to create opto-electronic integrated circuit (OEICs). This is due to the fact that cleaving of the semiconductor is an essential step in manufacturing conventional lasers.

In 1997 a reproducible manufacturing process was developed in the laboratory for III-V semiconductor technology of the TUE group Electronic Devices to fabricate wet chemically etched mirror lasers (WCEMLs) monolithically integrated with a monitoring photodetector. The WCEML is also an edge emitting device, but its mirrors are obtained by wet chemical etching rather than cleaving. It has been found that for cleaving the length of the device should be 1.5 times its thickness. For etched mirror lasers there are no limits on the minimum cavity length. These devices can therefore be a part of OEICs and they can be made quite small (a cavity length of 30 µm has been reported [8]).
This thesis describes two important topics:

1. Manufacturing and characterisation of GaAs/Al$_x$Ga$_{1-x}$As WCEMLs. We use mask set designed for fabricating WCEMLs, for which four lithography steps are required. As we will see, short cavity WCEMLs with a multiple quantumwell active layer can emit light at two or three different wavelengths. The difference in wavelength of the two peaks appearing in the spectrum can be as high as 40 nm.

2. Manufacturing and characterisation of a GaAs/Al$_x$Ga$_{1-x}$As WCEML monolithically integrated with a monitoring detector. This basic, though very important opto electronic integrated circuit (OEIC) proves that the WCEML can be integrated with other devices. We will see that the monitoring detector generates a photocurrent almost proportional to the laser output, and that the laser output versus current curve can also be measured using the integrated photodetector. We have compared the spectral behaviour of the integrated WCEMLs with that of a separate non-integrated WCEMLs in the same material system.

The thesis is organised in the following way. In chapter 2 we describe the WCEML and its monolithic integration. This chapter also describes the used material systems. Chapter 3 is a thorough discussion of the manufacturing process for the WCEML and the additional steps required to integrate the WCEML with the photodetector. Chapter 4 deals with the characterisation of the WCEMLs with or without the detector. The conclusions are drawn in chapter 6.
Chapter 2

Devices

2.1 The Wet Chemically Etched Mirror Laser

A laser can be regarded as an optical waveguide with gain, having mirrors at its two ends to form a Fabry Perot resonator cavity. At least one of the mirrors is only partially reflecting, to allow light generated in the waveguide to leave it. Light is generated by bringing the waveguide in such a state that it no longer attenuates the light inside it, but rather amplifies the light. This is done by pumping the material of the waveguide. In a semiconductor laser pumping is done by injecting charge carriers in the active layer (which is that part of the waveguide with higher refractive index).

The ridge waveguide laser is a well known device, and has become very popular due to its uncomplicated manufacturing process. A self aligned process is used as it requires one lithography step. The mirror facets are obtained by cleaving separate devices out of one processed wafer. The cleavage planes are smooth enough to serve as mirror planes. See for a full detailed description of the manufacturing and characterisation of cleaved mirror ridge waveguide lasers [2]. The major drawbacks of these devices is the impossibility to monolithically integrate them with other devices.

To integrate ridge waveguide lasers cleaving should be avoided until dicing and mounting. In this report a method is presented to obtain the mirror facets by wet chemical etching. The devices obtained are referred to as Wet Chemically Etched Mirror Lasers (WCEMLs [7]). Such a device is depicted in fig. 2.1

The vertical waveguide structure is obtained by the epitaxial layer structure since the GaAs active layer has a higher refractive index than the two Al$_x$Ga$_{1-x}$As cladding layers which surround the active layer. The light is confined to the region with highest refractive index. To obtain more efficient waveguiding Graded Index Separate Confinement Heterostructures (GRINSCH) were used for our devices.
Lateral waveguiding is obtained by etching a ridge up to about 0.3-0.4 μm above the active layer. The lightwaves in the active layer also propagate partially through the cladding layers and are affected by the change of thickness. Optically this results in a higher effective refractive index in the area under the ridge than in the area outside the ridge. In this manner, optical confinement is ensured.

An insulator is applied everywhere except on top of the ridge. The p-metallisation only contacts the semiconductor on top of the ridge thus charge carriers are only injected in the active layer area under the ridge. Although this current confinement results in gain guiding, the intensity distribution is mainly the result of the index profile. Therefore WCEMLs are of the index guided type ([1] page 321).

The emitted lightbeam is parallel to the surface of the semiconductor. Just like with any other edge emitting laser the beam emitted by a WCEML is non-circular but elliptic.

WCEMLs can be made from a variety of layer structures. In this report multiple quantum well structures as well as a structure with a GaAs bulk active layer, i.e. a GaAs layer of several ten nanometers thick, have been processed and characterised (see §2.3).

### 2.2 Integration with detector

In many applications an edge emitting lasers is used in conjunction with a photodetector to monitor the laser optical power to stabilise the optical power or the emitted wavelength. In order to increase performance and reliability and to reduce the amount of assembly steps it is attractive to integrate the detector with the laser, creating a basic Opto-electronic Integrated Circuit (OEIC).

When a ridge waveguide laser structure is reversed biased (or not biased at all) a depletion layer is established in the active region. When this region is exposed to
light, electron-hole pairs will be generated, generating a photocurrent proportional to the intensity of the light. The light could be coming from a ridge waveguide laser integrated next to it (see fig. 2.2).

Figure 2.2: Two laser devices next to each other

Such an approach has been followed by K. Iga et al. [16]. The laser beam is coupled into the reversed biased device (on the left), generating a photocurrent proportional to the laser output. The problem is that a part of the light falling on the reversed biased device is reflected back into the laser. This light will interfere with the light still in the laser. The performance of the laser is therefore negatively affected. Also the laser lifetime will be reduced since optical damage of the mirrors increases.

The problem can be solved by tilting the mirror facet of the reversed biased device which is nearest to the laser. The reversed biased device then becomes a true detector (i.e. a device intended to be used as a detector rather than as a laser). Light is still coupled into the detector because of its waveguide structure, provided that the angle of the facet toward the vertical is not too large. The light reflected by this tilted (overcut) facet is not coupled back into the laser. This structure is depicted in fig. 2.3.

Figure 2.3: A laser and a detector on one substrate

This approach has been followed by N. Bouadma et al. ([12,14]), who have done the integration on a GaAs/Al$_x$Ga$_{1-x}$As based layer structure. An integration of a laser with a detector in the InGaAsP/InP material system has been reported by
H. Saito et al. [15] and N. Bouadma [13]. Also a detector with both mirror facets tilted has been reported by K. Dütting [17].

All these approaches have in common that the mirror facets as well as the tilted detector facet have been obtained by a dry etch method. This could either be Ion Beam Etching ([12,14]), Reactive Ion Etching ([13,15]) or Reactive Ion Beam Etching ([17]). Distances between devices were a few ten μm’s.

In this report an approach has been chosen to obtain the tilted facet by a wet chemical etching process. Wet chemical etching introduces less damage to the etched surface than any of the dry etch methods. The device processed with this method is shown in fig. 2.4.

The narrow groove between the two devices results from the process used and cannot be avoided in wet chemical etching processes.

The currents we can expect from such a detector are in the order of micro amperes (μA), which is very small. Bouadma, et al. [12,14] have found efficiencies of 5 μA/mW for a detector integrated with a laser in the GaAs/Al₂Ga₃As₃ system.

Characterisation of such devices in pulse mode without having to suffer from external sources of interference has been proven to be very difficult.

### 2.3 Layer structures used

The multiple quantumwell Graded Index Separate Confinement Heterostructure (GRINCH) has either two or three GaAs quantumwells with a thickness of 7 nm each separated by a 15 nm thick layer of AlₓGa₁₋ₓAs. The layers are grown with solid source molecular beam epitaxy (MBE). Silicon (Si) has been used as the n-dopant, while beryllium (Be) is the p-dopant. The superlattice buffer layer (SLB) ensures that a laser processed out of this material has a lower threshold current,
higher external differential quantum efficiency and narrower spectral lines ([3] page 4). The overall layer structure is shown in fig. 2.5. Detailed aluminum profiles can be seen in figs. 2.6 and 2.7.

**MQW Laser structure**

Figure 2.5: Aluminium, donor and acceptor concentration as a function of the depth
We have also used material with a bulk active layer (bulk material, fig. 2.8). This material has the same structure as the multiple quantumwell structures, except that the quantumwell active layer of the latter structures have been replaced by a 50 nm thick of unintentionally doped GaAs. The active layer is located 1.74 $\mu$m below the surface, instead of 2.1 $\mu$m for the multiple quantumwell structure. This results from the fact that the top p-GaAs layer in the bulk material is 0.4 $\mu$m thinner than the same layer in the material with the multiple quantumwell active layer. All materials used are grown on (100)-substrates.
Material with two and three quantum wells has been used to process WCEMLs. The material with the bulk active layer has been used as well for WCEMLs as for the integrated laser and detector. All structures have been grown by molecular beam epitaxy in the Physics Department of Eindhoven University of Technology. All manufacturing processes have been carried out in the laboratory for III-V semiconductor technology of the group Electronic Devices of Eindhoven University of Technology.
Chapter 3

Manufacturing process of the WCEML

3.1 Introduction

To manufacture the WCEML (wet chemically etched mirror laser) four lithography steps are required:
- etching the ridge waveguide and deposition of the silicon nitride passivation layer
- evaporation of the p-contact
- opening windows in the passivation layer for the mirrors
- etching of the mirrors.

After these steps the wafer is polished until a thickness of about 120 μm has been reached. Then the n-contact is evaporated on the backside of the wafer. The n-contact is then alloyed. Cleaving the wafer in separate bars concludes the manufacturing process.

For the integration with a photodetector one extra step is required to obtain the tilted detector facet. This step is done between the step to open the windows in the passivation layer and the step to etch the laser mirrors (see §3.6.2)

This chapter describes the manufacturing process for the WCEML and for the integrated laser and detector in considerable detail. The integrated laser and detector will be referred from now on as the LD-set.

3.2 Mask set

There are four different mask involved in the process. These mask correspond with each of the four lithography steps required for the WCEML-process:
- mask 1: mesa (light field)
- mask 2: p-metal (dark field)
- mask 3: silox (dark field)
- mask 4: mirror (dark field)

Each mask contains four areas which correspond with the different devices which can be created with these masks (see fig 3.1). Each unit cell has a size of 1 cm × 1 cm.

![Figure 3.1: Mask layout](image)

The WCEML part of the mask defines devices with ridge lengths of: 750 µm, 500 µm, 300 µm, 200 µm, 100 µm, 75 µm, 50 µm, 30 µm, 20 µm, 10 µm and 7 µm and ridge widths of 10 µm, 6 µm and 4 µm. This enables us to manufacture devices and to investigate their properties as a function of the length and the width.

The cleaved laser part of the first mask contains stripes for cleaved mirror lasers. The stripes on the WCEML part and the LD-part of this mask make an angle of 40° with the [0\(\bar{1}\)1] direction (see §3.5.4)

The first mask is aligned such that the cleaved mirror laser stripes are parallel to the major index ([0\(\bar{1}\)1]-direction) of the wafer. The other masks are aligned using specific alignment marks.

### 3.3 Cleaning

Before application of resist the wafer should be free of contaminants and should be dry. Also the thin layer of native oxide on the surface needs to be removed. To remove this native oxide the wafer is rinsed in a fresh solution containing 5 ml NH\(_3\)-solution (ammonia) and 50 ml deionized water (D.I. water) at room temperature for one minute. After that the wafer is rinsed in reverse osmose (R.O.) water and then in D.I. water. Rinsing in D.I. water is performed until the water has a re-
sistance of 5 MΩ. Then the wafer is blown dry with dried N₂. Rinsing in ammonia solution is omitted when a passivation layer has been applied. The wafer is cleaned by rinsing it in acetone for 2 minutes followed by rinsing it in isopropanol for 2 minutes. Rinsing in boiling chloroform (as described in [2]) is no longer done. The wafer is then blown dry again. To ensure complete evaporation of moisture that may be present on the wafer a baking step on a hot plate at 105°C for 5 minutes is used.

3.4 Resist processes

For lithography the resist used is Hoechst AZ 5214E photoresist. This resist can be used for normal positive lithography as well as the image reversal process. The latter process is not used for the manufacturing of WCEMLs. However, using some of the properties of AZ 5214E a profile for lift-off purposes can be created (see §3.4.2).

3.4.1 Normal resist process

This process is used to define patterns for wet or dry etching. After cleaning the wafer (see §3.3) AZ 5214 resist is applied by spinning at 5000 rpm during 30 seconds. This leads to a uniform thick layer of about 1.4 μm. To evaporate almost all solvents in the resist spinning is followed by a five minute soft bake at 95°C on a hot plate.

Aligning of the mask is done with a Karl Süss MJB 3 mask aligner. The resist is exposed for five seconds with the UV400 filter (power density 12 mW/cm²).

Development of the resist is done for 30 seconds in a fresh solution of 60 ml AZ-developer and 60 ml D.I. water at room temperature. After development the wafer is rinsed in D.I. water and dried.

The result of this work should be a pattern of resist with uniform color and sharp corners. The pattern is inspected with a Polyvar optical microscope while the thickness is inspected using a Tencor Alphastep 2000 profiler. When patterning is followed by wet chemical etching the wafer should be baked for 10 minutes at 105°C to improve adhesion of the resist.

3.4.2 Resist process for lift-off

This process is used when the application of the resist pattern is followed by a deposition or an evaporation step. After deposition or evaporation the resist is dissolved in acetone, causing the material on to of the resist layer to be removed as well. This process, called a lift-off process, is depicted in fig. 3.2.
To make this approach successful two requirements have to be met:

1. The deposition or evaporation process should be anisotropic, i.e. there should be no tendency for undercut sidewalls to be covered with the deposited material. An undercut sidewall is a sidewall of a resist profile or an etch groove having a negative slope. If the sidewall has a positive slope, it is called overcut (see fig. 3.3).

2. The resist profile should have an undercut sidewall.

The resist used for this process is again AZ 5214E photoresist, which can also be used for an image reversal process. In an image reversal process the resist is after application first exposed with the mask. A bake of 3 minutes at 120°C is then applied to crosslink the exposed areas of the resist. These areas will become indissolvable in the developer. An exposure of the entire resist layer makes the unexposed area soluble in developer, leaving the crosslinked areas behind. The crosslinked areas correspond with the negative pattern. In a lift-off process the phenomenon of crosslinking in exposed areas due to a bake at 120°C is used.
After spinning and baking the resist it is exposed entirely (flood exposure) for 2.6 seconds with the dark UV300 filter. Since the top of the resist layer is exposed to more light energy than the bottom the top of the layer will show more crosslinking. As a result the top of the resist layer will become less soluble in AZ-developer than the bottom when the resist is baked for 5 minutes at 105°C. A 31 seconds mask exposure with the dark UV300 filter defines the pattern (optical power 12 mW/cm² bf measured with the UV400 filter. When the resist is then developed an underetch effect will appear since the bottom of the resist layer dissolves easier than the top. An undercut profile suitable for lift-off is thus achieved (fig. 3.3a).

If wet etching precedes the deposition or evaporation process the resist should be baked for 10 minutes at 105°C to improve adhesion. This does hardly affect the undercut profile.

Optimising this resist process means finding a compromise between the amount of undercut and the development time. Generally it can be said that the larger the development time the greater the amount of undercut. A larger development time, however, does impair the resist adhesion. It is therefore desirable to keep the development time shorter than 2 minutes.

The development time is highly dependent on the flood-exposure time. It is found that a flood exposure time of 2.6 seconds results in a development time of 85 seconds, which is long enough to get an undercut profile suitable for lift-off. The adhesion does not suffer too much. Making the flood exposure time one second longer yields a development time of over three minutes, resulting the resist pattern to come loose from the substrate. The profile of the remaining resist shows a high degree of undercut.

Due to degradation effects of the mercury lamp in the mask aligner, the result of this resist process will vary. Flood exposure time determines the development time for a great deal. Regular optimisation is therefore recommended.
3.5 Process overview

3.5.1 Etching the ridges

The wafer is patterned with AZ 5214E resist prepared for lift-off (see §3.4.2). For mask exposure the first mask (mask 1: mesa) is used. Alignment is done such that the major index ((110)-direction) is parallel to the cleaved laser stripes. The etched mirror laser stripes then make an angle of 40° with the major index. This is done for two reasons:

1. the mirrors, which are perpendicular to the ridges, then make an angle of 50° with the major index which is needed to obtain vertical mirrors (see §3.5.4).

2. to ensure that the sidewalls of the ridges are overcut (otherwise the sidewalls will not be covered by the metallisation for the p-contact).

After patterning the wafer is baked for 10 minutes at 105°C to improve adhesion of the resist. After that the resist height, about 1.4 μm, is measured using the Tencor Alphastep 2000. The ridges are etched in a phosphoric acid solution (H₃PO₄:H₂O₂:CH₃OH = 20:20:60 ml) at 0°C. This etchant has an etch rate of about 0.35 μm/min. The exact etch rate is determined by processing a GaAs dummy wafer the same way as the real sample. Etching is done until the mesas are 0.3-0.4 μm above the active layer. If the ridges are etched too deep the internal losses at the base of the ridges increases. If the ridges are not etched deep enough the lateral index difference decreases, which may result in a gain guided laser (see [3] page 12). For the multiple quantumwell structure, a ridge height of 1.8 μm is required, while for the bulk active layer structure a ridge height of 1.4 μm is required since the active layer is at 1.74 μm from the surface. The under etch effect result in ridge widths which are about 3.5 μm less than the width on the mask (10 μm on the mask becomes 6.5 μm on the wafer, 6 μm on the mask becomes 2.5 μm on the wafer and 4 μm on the mask becomes 0.5 μm on the wafer, which is very narrow). For the bulk active layer structure this underetch is about 1.4 μm.

After etching the wafer is rinsed firmly in D.I. water and blown dry. The etch depth is checked with the Tencor Alphastep 2000. The resist height (measured before etching) is subtracted from the second measurement to find the ridge height. It has been found that the resist is hardly attacked by the wet etchant. The passivation layer is then deposited on the wafer with the resist pattern still on. We have chosen to use silicon nitride (SiNx) deposited with Plasma Enhanced Chemical Vapour Deposition (PECVD) at 100°C (silicon nitride is in fact Si₃N₄, but this material can only be deposited by high temperature Chemical Vapour Deposition. Silicon nitride deposited with PECVD contains also an amount of hydrogen).
Normally, one would choose for SiO₂ as the passivation layer since its dielectric constant is lower than the one for Si₅X. Parasitic capacitances resulting from the passivation layer will then be smaller.

At the time of deposition the Si₅X layers were of more uniform quality than silicon dioxide (SiO₂) layers deposited with PECVD. According to Bruijsten [6], silicon nitride has a refractive index of 2.4, a dielectric constant of 5.8, and a resistivity of 12.5 Ω·cm, implicating that the quality of the silicon nitride is sufficient for use as the passivation layer. A layer of about 250 nm thick is deposited.

If SiO₂ is used as the passivation layer resist application in all succeeding steps should be preceded with the application of HMDS-primer. The primer enhances adhesion of the resist on the SiO₂ layer. With Si₅X this is not necessary.

After deposition the resist has to be removed (lift-off). The Si₅X though has the tendency to cover up the entire resist profile. However, ultrasonic vibration in a bath of acetone for 2 minutes results in a good lift-off. The remaining Si₅X on the semiconductor does not show excessive defects. The wafer should not be soaked in (boiling) acetone before ultrasonic vibration is attempted, otherwise lift-off will fail completely.

The result of all these steps is depicted in fig 3.4. The passivation layer is everywhere except on top of the ridges.

![Passivation layer](image)

**Figure 3.4: Wafer after performing the ridge etching**

It should be noted that vd Heuvel [3] used two lithography steps to create this structure. After mesa etching the resist was removed. Then the passivation layer was deposited using PECVD. Windows were then opened in the pasivation layer using standard lithography and wet etching in buffered HF. These two steps have now been combined into one.

### 3.5.2 Evaporation of the p-contact metallisation

Before lithography the silicon nitride layer has to be baked to remove all moisture from it. Baking is done in an AST SHS100 Rapid Thermal Annealer (RTA)
at 450°C for 10 minutes in an argon ambient. Argon is used since this gas is completely inert and therefore does not attack any of the materials on the wafer. Heating up a wafer in the presence of some gases is referred to as annealing. The complete steps for this RTA process are listed below:

- Load wafer
- Evacuation of the chamber followed by purging with N₂, 15 l/min
- Evacuation of the chamber followed by purging with argon
- Warming up to 100°C
- Heating up from 100°C to 450°C in 10 seconds
- Leaving the temperature at 450°C for 10 minutes
- Cooling down to 100°C
- Evacuation and purging with N₂ 15 l/min (done twice)
- Unload sample

Since silicon nitride has a tendency to attract moisture this bake should be followed immediately by the lithography for the p-contact. Moisture in the silicon nitride will result in bubbles in the p-metallisation after alloying this metallisation. A resist profile for lift-off is applied (see §3.4.2). The mask used is mask 2 labeled 'metal'. This mask is aligned using the alignment marks on the mask and the ones which have been etched along with the ridges. The mask should be aligned in such a way that the ridges are completely visible through the windows in the mask.

It has been suggested by vd Heuvel [3] to bake the wafer for 5 minutes at 105°C to evaporate all moisture which may be on the wafer after lithography. We have not got any problems by not doing so.

The actual evaporation is done in a Leybold LH560UV evaporator using e-beam evaporation. The following metals are used: 50 nm Ti, 20 nm Pt and 200 nm Au. After alloying this metallisation system, good ohmic contact are obtained ([2] page 26). The evaporation rate is about 0.2 nm/sec.

After evaporation lift-off takes place. This is done by ultrasonic vibration of the wafer in a bath of acetone, or by spraying acetone from the spray bottle on the wafer. Boiling acetone has not been required to obtain good lift-off. If lift-off is troublesome one should watch the resist profile in a scanning electron microscope (SEM).

The result of these steps are depicted in fig. 3.5. We have also included two SEM-pictures of the p-metallisation (figs. 3.6 and 3.7). The SEM picture are made with a JEOL 6400-F Scanning Electron Microscope. What can be seen is that the sidewalls of the ridge are covered. The headwalls, however, are not because these walls have a slightly undercut profile.

A problem which arose is the fact that the devices with the 4 μm wide ridges did not operate, i.e. no current flow was observed. This may be caused by the fact that the p-metallisation does not contact the semiconductor, as it can be seen in the SEM-picture of fig. 3.7.
3.5.3 Opening windows in passivation layer for mirrors

Prior to the lithography step needed for etching the mirrors, openings in the SiN$_x$ layer need to be made. Pattern definition is done with AZ 5214E processed according to the normal recipe (see §3.4.1). The mask used is labeled mask 3:silox and is aligned using the alignment marks in the mask and on the wafer. Alignment is correct if the entire metallisation pattern is covered by the mask.

The windows are opened by plasma etching (see appendix A). It could also have been done in a buffered hydrogen fluoride (HF) solution. If done so the wafer should be baked for 10 minutes at 105°C before etching. With plasma etching the resist pattern is followed more closely.
Plasma etching is done for 5 minutes. After that the resist is removed by rinsing the wafer in acetone for two minutes followed by rinsing the wafer in isopropanol for two minutes. Since the resist has been exposed to a plasma, some of it will be hard to remove. In that case brown sweeps appear on the wafer after cleaning in acetone and isopropanol (two minutes each). The wafer should then be exposed to an oxygen plasma for five minutes to remove all resist. This also oxidises the surface of the semiconductor but this part is etched away in the next processing step. After resist removal the wafer should look the way depicted in fig 3.8.

It is possible to omit the lithography for opening the windows and use the metallisation pattern as the mask.
3.5.4 Etching the mirrors

Before etching the mirrors and after cleaning the wafer a resist pattern is applied using the normal process (§3.4.1). A hard bake for 10 minutes at 105° prepares the wafer for etching. The mask used is labeled mask4: mirror. It shows the same patterns as on mask 3:silox (see the previous section) except that these patterns are a bit smaller to take into account the under etch effect. Aligning of this mask is done solely on the alignment marks on the mask and on the wafer. If aligned properly the p-metallisation patterns are covered entirely by the mask. Slight misalignment of the mask may result in etching under the metallisation.

The research on wet chemically etching of grooves with vertical walls has been performed by vd Heuvel [3,4]. Etching is done in a phosphoric acid solution (H₃PO₄:H₂O₂:CH₃OH = 30:30:30 ml) at 20°C. This etching process is highly diffusion limited, which means that the etch rate is determined by the speed at which reactants are moved towards the wafer and reaction products are moved away from the wafer. It has been found by experimenting with numerous etch solutions that if the pattern defining the mirrors makes an angle of 50° to the major index (see fig. 3.9) and etching is done for 85 seconds the etch groove has vertical and smooth sidewalls. The resulting etch depth is between 3 μm and 5.5 μm. If the etch time is too short the walls will have overcut sidewalls. If the etch time is too long undercut sidewall will be obtained. In all cases, a high amount of trenching is observed, i.e. the bottom of the etch groove is not flat. This is typical for a diffusion limited wet etching process. The amount of underetch is under these circumstances almost equal to the etch depth.

![Figure 3.9: Position of the ridges with respect to the crystal direction](image)

A possible explanation of these results can be as follows: when a diffusion limited etch solution is used to etch stripes parallel to the [011] direction, it results in negative slope walls (dove tail shape). By allowing longer time of etch there is a tendency to obtain positive slope walls. Similar results over the dependence of the shape of the etched groove on the etch time are reported in the literature [10,11].
Theoretically vertical side walls are obtainable with any etch solution when aligning at 45° towards the [011] and the [0\bar{1}1] directions. In practice some experimental research is required before obtaining this result. In our case the orientation of 50° towards the [011] direction means that the stripe is closer (40° only) to the [011] direction than to the [0\bar{1}1] direction. In this case there will be a tendency for giving slightly negative slope walls. This is compensated by the tendency of diffusion limited etch solution to produce positive slope walls. The result of this step is depicted in fig. 3.10.

![Laser mirrors](image)

Figure 3.10: Wafer after etching the mirrors

In some cases, etching under the p-metallisation took place. This may have resulted in mirror quality to be deteriorated. Also, it seems to make difference whether to keep the sample upside down during etching or not. In the first case, the mirrors of the shorter devices have shown some bending, i.e. the etch walls were not completely straight.

After etching the mirrors step the p-metallisation is alloyed in the RTA similar to the way the oxide is baked. The stable temperature is 400°C and is held for one minute. Argon is used as the ambient gas since it does not react with any of the materials on the wafer. If moisture is trapped in the passivation layer under the p-metallisation, it will try to find its way out during alloying. The metallisation will be lifted, resulting in bubbles.

### 3.5.5 Polishing, n-metallisation and dicing

Polishing the wafer until a thickness of about 130 \mu m is done for two reasons. The first is to enable dicing of the wafer parallel to the mirrors (which are not parallel to a cleavage plane). The second is to reduce bulk series resistance. The way polishing is done is described by Wellen ([2] page 27).

For the n-contact the following system of metals is evaporated using e-beam evaporation (Leybold): Ge (20 nm), Ni (15 nm) and Au (200nm). The backside n-contact is alloyed exactly the same way as the p-contact.
Breaking is done in the following way. First the wafer is attached to a plastic foil using AZ 1505 photoresist spun on the foil at 2000 rpm for 15 seconds. After that AZ 1505 resist is spun on the wafer at 5000 rpm during 30 seconds. This is done to prevent the mirrors from being damaged during dicing. To harden the resist the foil with the wafer is laid on a 95°C hotplate during one minute (not longer to prevent the foil from melting).

Scribing is done using a Loomis diamond scriber. Full line scribes between rows of devices are made with a needle pressure of 1.7 bar. After that the wafer is broken in bars of several devices. The WCEMLs are not mounted for characterisation purposes.

In some cases, the wafer does not break between rows of devices. This may have resulted in unwanted reflections from mirrors of opposite devices.

3.6 Integration of the WCEML with a photodetector

The processing for the LD-set involves the addition of one extra step. After etching the windows in the passivation layer and before etching the mirrors the tilted detector facet has to be created. This is done by etching a groove with overcut sidewalls and using one of these walls as the detector facet.

3.6.1 Mask set

The masks are the same as those used for the WCEML. One mask is added (mask 5:detect) to define the groove for the detector. The laser+detector section of the masks is used (see fig. 3.1 on page 11). This section defines lasers with a ridge length of 300 μm and ridge widths of 10 μm, 6 μm and 4 μm. These ridges are aligned with detector ridges having a width of 20 μm and lengths of 200 μm, 400 μm, 800 μm and 1600 μm respectively. The ridge stripes again make an angle of 40° with the [1T0] direction.

3.6.2 Detector facet

Processing of the LD-set is the same as processing WCEMLs up to the etching of the mirrors (see §3.5.1, §3.5.2 and §3.5.3). After opening of the windows in the passivation layer a pattern of AZ 5214E resist is created using the normal process (see §3.4.1). The mask used is labeled mask5: detect. It defines open stripes between devices with narrow ridges (lasers) and devices with wider ridges (detectors). Aligning is done using the alignment marks and is correct when the metalli-
sation patterns are covered entirely by the mask. After development the wafer is baked for 10 minutes at 105°C to improve the resist adhesion.

Etching of the groove is done in a sulfuric acid solution (H₂SO₄:H₂O₂:H₂O=10:10:100 ml) at 20°C. This etchant has an etch rate of 0.75 μm/min and etches a groove with walls making an angle of about 30° with the vertical. Etching is done during 2 minutes 30 seconds. After removing the resist the wafer should look like depicted in fig. 3.11

![Figure 3.11: Wafer after etching the detector groove](image1)

The groove is nearer to the detector than to the laser. The tilted sidewall nearest to the detector will be used as detector facet. Fig. 3.12 shows a SEM-picture of such a facet. The cleavage plane on the right makes an angle of 40° with the etched groove, so the slope is less pronounced as seen in the picture.

![Figure 3.12: SEM picture of the detector facet](image2)
3.6.3 Laser mirrors

This step is similar to the corresponding one in the WCEML process (see 3.5.4). The mask used is labeled mask 4:mirror and has wide stripes and narrower stripes. Alignment is correct when no metallisation is visible, and one of the etch walls made in the previous step is visible through the narrower stripe in the mask.

After processing according to the steps described in §3.5.4 the wafer looks the way as depicted in fig. 3.13

![Laser mirrors](image)

**Figure 3.13: Wafer after etching the mirrors**

A groove is created with near the laser a vertical wall (the mirror) and an overcut wall (the detector facet). The smaller groove in the middle is a result of the two etch processes and should be regarded as an unavoidable side effect. No harm is expected from it.

Fig. 3.14 shows a SEM-picture of that structure. The device with the wide ridge is the detector, the one with the narrower stripe is the laser. The distance between the detector and the laser is 60 μm.

Finishing the wafer is done the same way as for WCEMLs and has been described in §3.5.5. We have chosen to mount some LD-chips, in order to allow characterisation of these devices in continuous wave mode (CW).

Mounting is done in dual in-line packages (DIL) with 16 pins cut in half. Each half package can contain two connected LD-sets. The chips are attached with silver cement (Epo-tek) onto the package. The cement also transfers heat generated in the lasers to the package. Gold wires connect the devices with the pins of the package.

The pinout of the packages is depicted in fig. 3.15.

For test reasons only lasers with 10 μm wide ridges and there inline detectors have been connected. See for a process overview for the WCEML and the LD-set appendix A.
Figure 3.14: *SEM picture of the etched groove*

Figure 3.15: *Package with mounted LD-set*
Chapter 4

Characterisation of the devices

4.1 Characterisation of the WCEMLs

The lasers have been subjected to the following characterisations:
- LI-curve, i.e. the light output versus the current
- spectra.

From the LI-curves the following data are extracted:

1. Threshold current $I_{Th}$ defined as the current at which the device shows laser action, i.e. stimulated emission becomes dominant over spontaneous emission.

2. Threshold current density $J_{Th} = I_{Th}/LW$, $L$ is the length of the ridge and $W$ is the width of the ridge.

3. Differential efficiency $\eta_D$, which is defined as

$$\eta_D = \frac{dP}{dI} = \frac{1}{L} \ln \frac{1}{R}$$

In eq. 4.1 $E_g$ is the bandgap energy of GaAs (assumed to be 1.424 eV), and $\eta_i$, the internal quantum efficiency, which according to Wellen [2], can be assumed unity. $L$ is the length of the cavity and $R$ the reflectivity of the mirrors. We assume $R = 0.3$ [2]. The total internal absorption $\alpha_i$ can be found by solving eq. 4.1. This yields

$$\alpha_i = \frac{1}{L} \ln \frac{1}{R} \left[ \frac{\eta_i}{\eta_D} - 1 \right]$$

(4.2)
The LI-curves have been measured without mounting the devices. The current was measured by measuring the voltage across a 50Ω resistor in series with the device under test. The light output was measured with a calibrated silicon photo-detector, which was reversed biased with a 5V DC voltage source. The data were recorded on a HP oscilloscope connected to a PC. A LABVIEW program was used to read in the data. The lasers were operated in pulse mode at a frequency of 10 kHz and a pulse duration of 1 µs. This has been done because the detector is too slow to handle pulses shorter than 1 µs.

The characterisation has been carried out on devices with two quantum wells and with three quantum wells as well as devices with a bulk active layer. Each quantum well is 7 nm wide and is separated by 15 nm of Al0.2Ga0.8As, whilst the GaAs bulk active layer is 50 nm thick. Optical confinement of light has been achieved by using a graded index separate confinement heterostructure (GRINSCH) between the Al0.7Ga0.3As layers (see figs. 2.6 and 2.7 on page 8).

4.2 WCEMLs with two quantum wells

4.2.1 LI-curves

Only the devices with ridges of 100 µm and longer have been characterised. The shorter devices did not show laser operation. This may be due to the poor quality of these device mirrors. We have observed that these mirrors are not straight. This may result from the fact that the wafer was in an upside down position during mirror etching.

The LI-curves are depicted in appendix B fig. B.1 and fig. B.2. What can be seen on these curves is that the slope decreases with increasing current. This is caused by the fact that the devices heat up more at higher currents, increasing the internal losses. The data in tables 4.1 and 4.2 are extracted from the curves. The quantity $dP/dI$ is extracted from the lower part of the curve.

<table>
<thead>
<tr>
<th>$L$ (µm)</th>
<th>$I_{Th}$ (mA)</th>
<th>$dP/dI$ (mW/mA)</th>
<th>$J_{Th}$ (kA/cm²)</th>
<th>$\eta_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>48</td>
<td>0.088</td>
<td>4.80</td>
<td>0.12</td>
</tr>
<tr>
<td>200</td>
<td>25</td>
<td>0.056</td>
<td>1.25</td>
<td>0.079</td>
</tr>
<tr>
<td>300</td>
<td>22</td>
<td>0.032</td>
<td>0.73</td>
<td>0.045</td>
</tr>
<tr>
<td>500</td>
<td>28</td>
<td>0.10</td>
<td>0.56</td>
<td>0.14</td>
</tr>
<tr>
<td>750</td>
<td>43</td>
<td>0.054</td>
<td>0.57</td>
<td>0.076</td>
</tr>
</tbody>
</table>

Table 4.1: Measured data for two quantumwell WCEMLs, stripewidth 10 µm
These data have been plotted out in figures B.3, B.4 and B.5.

Generally, the data show a lot of scattering, especially the data of the devices with 6 μm wide ridges.

For wide ridge lasers the threshold current should drop with decreasing ridge length. This effect has been observed by Wellen [2] for all multiple quantumwell structures. Only the lasers with only one quantumwell show from a certain point an increase in threshold current with decreasing length.

We deal with narrow ridge lasers with two quantumwells. The lasers with 10 μm wide ridge lasers show a decrease followed by an increase in threshold current with decreasing length. This kind of behaviour has also been seen by Wellen ([2] page 44) with single quantum well lasers with ridge width of 4.3 μm. The 6 μm wide ridge lasers do not show this behaviour at all. These latter devices also have a higher threshold current, resulting in much higher current densities.

Threshold current densities decrease with increasing length. This effect has also been observed by Wellen [2], but in our case the threshold current densities are much higher.

Differential efficiencies show a lot of scattering. The main reason for this is due to the quality of the laser mirrors. Over the wafer the mirror quality may vary a lot. On some places the mirrors are etched under the p-contact metallisation, while on other places this is not the case. Mirrors of short devices show a slight bend. The quality of the mirrors could be negatively affected by these phenomena, causing efficiencies of the devices to vary. Also irregularities in the ridge shape cause the efficiency of the laser to be negatively influenced. The lasers with 6 μm wide ridges suffer most from these irregularities.

<table>
<thead>
<tr>
<th>L (μm)</th>
<th>I_{TH} (mA)</th>
<th>dP/dI (mW/mA)</th>
<th>J_{TH} (kA/cm²)</th>
<th>η_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>31</td>
<td>0.12</td>
<td>5.17</td>
<td>0.17</td>
</tr>
<tr>
<td>200</td>
<td>40</td>
<td>0.10</td>
<td>3.33</td>
<td>0.14</td>
</tr>
<tr>
<td>300</td>
<td>54</td>
<td>0.025</td>
<td>3.00</td>
<td>0.035</td>
</tr>
<tr>
<td>500</td>
<td>42</td>
<td>0.034</td>
<td>0.84</td>
<td>0.048</td>
</tr>
<tr>
<td>750</td>
<td>32</td>
<td>0.093</td>
<td>0.71</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 4.2: Measured data for two quantumwell WCEMLs, stripewidth 6 μm
4.2.2 Multiple wavelength emission by quantumwell lasers

Lasers with a quantumwell structure as their active layer show multiple wavelength emission which can be explained as being due to the quantumwell behaviour of the active layer. In this section we present estimations of the energy levels inside the well. These estimations will be based upon the theory presented by Gasiorowicz [9]. This model contains a lot of simplifications, which will result in less accurate calculations for the emitted wavelengths.

For our model we will adopt the following assumptions:

1. The particles are bound in a two dimensional quantumwell structure (fig. 4.1). Its boundaries are at \( x = -a \) and \( x = a \). Inside the well the potential equals \( -V_0 \), outside the well it equals zero. The well itself is an undoped GaAs layer surrounded by undoped Al\(_{0.2}\)Ga\(_{0.8}\)As. Since the thickness of the quantumwell is 7 nm, \( a=3.5 \) nm.

2. The bandgap in the GaAs layer equals 1.424 eV (2.282\( \times \)10\(^{-19} \) J). The bandgap in the Al\(_x\)Ga\(_{1-x}\)As layer equals 1.424 + 1.247\( x \) eV. It is assumed that 60\% of the bandgap discontinuity appears in the conduction band [8]. So \( \Delta E_C = 0.747 \) eV and \( \Delta E_V = 0.50x \) eV. Since \( x = 0.2 \) we get \( \Delta E_C = 0.1494 \) eV and \( \Delta E_V = 0.1 \) eV.

3. The electron effective mass \( m_e = 0.0665m_0 \), The light hole effective mass \( m_{VL} = 0.08m_0 \) and the heavy hole effective mass \( m_{VH} = 0.45m_0 \), where \( m_0 \) is the free electron rest mass. These effective masses are assumed to be the same inside and outside the quantumwell.

![Figure 4.1: Potential function of a quantumwell with finite borders](image)

The idea is to solve Schrödinger's equation and to apply the boundary conditions for the configuration depicted in fig. 4.1 given that the energy of the particle \( E < 0 \), i.e. the particle is inside the well. This has been done in [9], pages 79-83.
This yields two conditions for the energy $E$ of the particles:

$$\kappa = q \tan qa$$

(4.3)

$$\kappa = -q \cot qa$$

(4.4)

with

$$q^2 = \frac{2m}{\hbar^2} (V_0 - |E|)$$

(4.5)

and

$$\kappa^2 = -\frac{2mE}{\hbar^2}$$

(4.6)

Eq. 4.3 describes the even solutions to the Schrödinger equation, while eq. 4.4 describes the odd solutions. The amount of solutions of eqs. 4.3 and 4.4 determine the amount of bound states in the quantum well. In case of the quantum wells in the active layer of the WCEMLs only two bound states are available for each particle. Eqs. 4.3 and 4.4 can only be solved by using some numerical methods (bisection algorithm). With the data given we can determine the energy levels in the quantum wells in the conduction band (electrons) and the valence band (light holes and heavy holes).

With the data given we find for the electrons the results given in table 4.3

<table>
<thead>
<tr>
<th>Energy level</th>
<th>Distance from $E_C$ inside the well (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\Gamma 1}$</td>
<td>0.045</td>
</tr>
<tr>
<td>$E_{\Gamma 2}$</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Table 4.3: Electron energy levels inside the conduction band

For the holes we find the data in table 4.4

<table>
<thead>
<tr>
<th>Energy level</th>
<th>Distance from $E_V$ inside the well (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$LH_1$</td>
<td>0.035</td>
</tr>
<tr>
<td>$LH_2$</td>
<td>0.10</td>
</tr>
<tr>
<td>$HH_1$</td>
<td>0.011</td>
</tr>
<tr>
<td>$HH_2$</td>
<td>0.041</td>
</tr>
</tbody>
</table>

Table 4.4: Hole energy levels inside the valence band
In table 4.4 $LH$ and $HH$ are the light holes and the heavy holes respectively. These energy levels are also depicted in fig. 4.2 (which is a highly simplified sketch of the real situation).

![Band structure of a GaAs quantumwell](image)

**Figure 4.2: Band structure of a GaAs quantumwell**

With these data we can calculate the energy difference of transitions between electrons and holes. Ideally, only the following transitions are allowed: $E_{\Gamma 1} - LH_1$, $E_{\Gamma 2} - LH_2$, $E_{\Gamma 1} - HH_1$ and $E_{\Gamma 2} - HH_2$. By using Planck’s law we find for the wavelengths the data in table 4.5

<table>
<thead>
<tr>
<th>Transition</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\Gamma 1} - LH_1$</td>
<td>824</td>
</tr>
<tr>
<td>$E_{\Gamma 1} - HH_1$</td>
<td>838</td>
</tr>
<tr>
<td>$E_{\Gamma 2} - LH_2$</td>
<td>745</td>
</tr>
<tr>
<td>$E_{\Gamma 2} - HH_2$</td>
<td>774</td>
</tr>
</tbody>
</table>

**Table 4.5: Wavelengths associated with the allowed transitions**
If we assume intermediate transitions to be allowed as well (strictly speaking this is not the case for the ideal quantum well), possible wavelengths are given in table 4.6.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\Gamma 1} - HH_2$</td>
<td>821</td>
</tr>
<tr>
<td>$E_{\Gamma 2} - HH_1$</td>
<td>789</td>
</tr>
<tr>
<td>$E_{\Gamma 2} - LH_1$</td>
<td>777</td>
</tr>
<tr>
<td>$E_{\Gamma 1} - LH_2$</td>
<td>790</td>
</tr>
</tbody>
</table>

Table 4.6: Wavelengths associated with the forbidden transitions

Similar results have been published in [8], but have been obtained by using some different assumptions.

### 4.2.3 Spectra of lasers with two quantum wells

As an example we will discuss the spectral behaviour of a two quantum well WCEML having a ridge length of 100 $\mu$m and a ridge width of 6 $\mu$m. At $I=60$ mA the spectrum of fig. 4.3 is observed.

![Figure 4.3: Spectrum at I=60 mA, 2QW laser L=100 $\mu$m, W=6 $\mu$m](image)

The devices spectrum show at this current a pronounced peak at $\lambda=843$ nm (from the $E_{\Gamma 1} - HH_1$ transition) and a less pronounced peak at $\lambda=788$ nm (from $E_{\Gamma 2} - HH_2$ transition). If the current is increased to 80 mA both peaks become more pronounced, as can be seen in fig. 4.4. The peak at $\lambda=843$ nm is accompanied by one at $\lambda=840$nm. This is due to more longitudinal modes appearing at the $E_{\Gamma 1} - HH_1$ transition.
Even a third peak appears at $\lambda = 804$ nm at a current of 160 mA (fig. 4.5). This peak can be related to the $E_{12} - H_{13}$ transition, although the deviation is quite large.

The peaks at $\lambda=840$nm and $\lambda=788$nm become more multimode.
This example illustrates the complexity of the spectral behaviour of the device. Fig. 4.6 shows the spectrum of a laser with two quantumwells operating at $I=200$ mA.

Figure 4.6: Spectrum at $I=200$ mA, 2QW laser $L=100$ $\mu$m, $W=10$ $\mu$m

Six peaks are seen. We have tried to relate these peaks to a corresponding transition (table 4.7). This is done by assuming that the peaks at the two longest wavelengths (843 nm and 833 nm) result from the $n = 1$ transitions and that the peak at the shortest wavelength (788) result from the $E\Gamma_2 - H\, H_2$ transition. The other peaks are thus assumed to result from intermediate transitions. Note that deviations between calculated data and measurement are considerable.

<table>
<thead>
<tr>
<th>Peak wavelength (nm)</th>
<th>Possible transitions involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>843</td>
<td>$E\Gamma_1 - H, H_1$</td>
</tr>
<tr>
<td>833</td>
<td>$E\Gamma_1 - L, H_1$</td>
</tr>
<tr>
<td>818</td>
<td>$E\Gamma_1 - H, H_2$</td>
</tr>
<tr>
<td>808</td>
<td>$E\Gamma_1 - H, H_2$</td>
</tr>
<tr>
<td>795</td>
<td>$E\Gamma_2 - H, H_1$</td>
</tr>
<tr>
<td>788</td>
<td>$E\Gamma_2 - H, H_2$</td>
</tr>
</tbody>
</table>

Table 4.7: Association of the emitted wavelength with a corresponding transition

Polarization dependent spectra measurements showed that all peaks in the spectrum are TE-mode polarized. This is to be expected as the GaAs quantumwells do not have any strain.

Whether a peak appears or not in the spectrum depends on the lightwave losses of the corresponding wavelength. Also the order of appearance with increasing current is determined by these losses. This may result in devices emitting only at
the $n = 2$ transitions and/or intermediate transitions as can be seen in the example depicted in fig. 4.7.

Figure 4.7: Spectrum at $I=160\ mA$, 2QW laser $L=100\ \mu m$, $W=10\ \mu m$
4.3 WCEMLs with three quantumwells

4.3.1 LI-curves

After processing only the devices with ridge widths of 10 μm showed laser action. The devices with 6 μm wide ridges collapsed within a few seconds. Overall processing of these devices is generally poorer than of the other devices. The LI-curves are depicted in fig. B.6. From these curves the data in table 4.8 has been extracted.

These data have been plotted out in figures B.7, B.8 and B.9.

<table>
<thead>
<tr>
<th>L (μm)</th>
<th>I_{Th} (mA)</th>
<th>dP/dI (mW/mA)</th>
<th>J_{Th} (kA/cm²)</th>
<th>η_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>49</td>
<td>0.083</td>
<td>6.53</td>
<td>0.12</td>
</tr>
<tr>
<td>100</td>
<td>43</td>
<td>0.1522</td>
<td>4.30</td>
<td>0.21</td>
</tr>
<tr>
<td>200</td>
<td>42</td>
<td>0.036</td>
<td>2.10</td>
<td>0.050</td>
</tr>
<tr>
<td>300</td>
<td>40</td>
<td>0.052</td>
<td>1.33</td>
<td>0.073</td>
</tr>
<tr>
<td>500</td>
<td>46</td>
<td>0.099</td>
<td>0.92</td>
<td>0.14</td>
</tr>
<tr>
<td>750</td>
<td>49</td>
<td>0.060</td>
<td>0.65</td>
<td>0.084</td>
</tr>
</tbody>
</table>

Table 4.8: Measured data for three quantumwell WCEMLs, stripewidth 10 μm

The threshold current does not vary very much with the length of the device. This has also resulted in an almost linear relationship between the current density and the reciprocal of the length. The threshold currents are higher than those of corresponding WCEMLs with two quantumwells. The differential efficiency shows a great deal of scattering. The differential efficiencies are generally higher than those of corresponding lasers with two quantumwells.

SEM-pictures (fig. 4.8) made of these devices reveal that the mirrors show more severe irregularities than the mirrors of the other devices (2QW and bulk). It is seen that black stripes become visible in the mirrors. These are holes in the mirrors. We don’t know why this is the case, also because the bulk active layer laser mirrors have been etched in the same etch bath.


4.3.2 Spectra

The spectra of the lasers with three quantumwells show similar behaviour as the ones with two quantumwells. The two different wavelength (852 nm and 798 nm) is seen with devices with a ridge up to 300 \( \mu \)m. For these long devices currents of up to 600 mA were allowed to flow (until the device collapsed). The spectrum is depicted in fig. 4.9.

Figure 4.9: *Spectrum at \( I=600 \) mA, 3QW laser \( L=300 \) \( \mu \)m, \( W=10 \) \( \mu \)m*

Similar phenomena have also been seen with lasers with 5 quantumwells (see [8]). The shifts between calculated and measured peak wavelengths is even larger.
4.4 Bulk active layer WCEMLs

Bulk active layer lasers are devices having a 50 nm thick undoped GaAs layer as the active layer. This layer is sandwiched between the AlGaAs cladding layers in a similar way as in multiple quantumwell structures. For vertical waveguiding the GRINSCH-structure has been applied. The devices have been processed according to the same recipe (chapter 3) as the multiple quantumwell lasers. Also the same characterisation methods have been applied to these devices.

4.4.1 LI-curves

Devices with a ridge length down to 50 μm have been characterised. The LI-curves of these devices are depicted in fig. B.10 and fig. B.11. From these plots the following data has been extracted.

<table>
<thead>
<tr>
<th>L (μm)</th>
<th>I\text{Th} (mA)</th>
<th>\frac{dP}{dI} (mW/mA)</th>
<th>J\text{Th} (kA/cm}^2</th>
<th>\eta_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>27</td>
<td>0.46</td>
<td>5.40</td>
<td>0.65</td>
</tr>
<tr>
<td>75</td>
<td>21</td>
<td>0.19</td>
<td>2.80</td>
<td>0.27</td>
</tr>
<tr>
<td>100</td>
<td>35</td>
<td>0.56</td>
<td>3.50</td>
<td>0.79</td>
</tr>
<tr>
<td>200</td>
<td>37</td>
<td>0.17</td>
<td>1.85</td>
<td>0.24</td>
</tr>
<tr>
<td>300</td>
<td>55</td>
<td>0.15</td>
<td>1.83</td>
<td>0.21</td>
</tr>
<tr>
<td>500</td>
<td>63</td>
<td>0.17</td>
<td>1.26</td>
<td>0.24</td>
</tr>
<tr>
<td>750</td>
<td>90</td>
<td>0.043</td>
<td>1.20</td>
<td>0.060</td>
</tr>
</tbody>
</table>

Table 4.9: Measured data for bulk active layer WCEMLs, stripewidth 10 μm

<table>
<thead>
<tr>
<th>L (μm)</th>
<th>I\text{Th} (mA)</th>
<th>\frac{dP}{dI} (mW/mA)</th>
<th>J\text{Th} (kA/cm}^2</th>
<th>\eta_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>77</td>
<td>0.089</td>
<td>17.1</td>
<td>0.125</td>
</tr>
<tr>
<td>200</td>
<td>40</td>
<td>0.10</td>
<td>3.33</td>
<td>0.14</td>
</tr>
<tr>
<td>300</td>
<td>54</td>
<td>0.10</td>
<td>3.00</td>
<td>0.15</td>
</tr>
<tr>
<td>500</td>
<td>57</td>
<td>0.052</td>
<td>1.14</td>
<td>0.073</td>
</tr>
<tr>
<td>750</td>
<td>80</td>
<td>0.051</td>
<td>1.78</td>
<td>0.072</td>
</tr>
</tbody>
</table>

Table 4.10: Measured data for bulk active layer WCEMLs, stripewidth 6 μm

These data have been plotted out in figures B.12, B.13 and B.14. The threshold current of these device are generally higher than those of two quantumwell devices resulting in higher threshold current densities. The threshold currents of these devices are comparable to those of corresponding three quantumwell
devices. Normally, one would expect the threshold current of a multiple quantumwell WCEML to be a factor of two smaller than the one for a corresponding WCEML with a bulk active layer.

Threshold current of devices with 10 μm wide ridges decreases with shorter cavities. This is also the case for the devices with 6 μm wide ridges. In both cases the threshold current rises sharply from a certain point. The 10 μm wide ridge lasers do have threshold current densities remaining generally lower than the ones for corresponding devices with 6 μm wide ridges. Threshold current density increases with decreasing lengths.

Also the differential efficiencies are larger than those of corresponding multiple quantumwell lasers. This is caused by the fact that a bulk active layer does not saturate with injected charge carriers. Differences, however, may also have been caused by differences in the quality of evaporated metal contacts. Especially the n-contact is suspected to have a high resistivity (see [2] page 53).
4.4.2 Spectra

It is expected that the phenomena of multiple wavelength emission do not occur in bulk active layer lasers since in a bulk active layer the carrier energy is not split up in distinct levels. What can be expected is the broadening of the spectra with increasing current.

As an example we show the spectra of a WCEML with a ridge of 300 $\mu$m $\times$ 10 $\mu$m (figs. 4.10 and 4.11).

Figure 4.10: Spectrum at $I=200$ mA of a bulk laser $L=300$ $\mu$m, $W=10$ $\mu$m

Figure 4.11: Spectrum at $I=200$ mA of a bulk laser $L=300$ $\mu$m, $W=6$ $\mu$m

Other devices show similar spectra. The spectra of shorter devices show more broadening than those of long devices. In some cases two peaks can be seen (fig. 4.12). This is the result of more longitudinal modes becoming dominant. The center wavelength of 870 nm corresponds with a energy of 1.425 eV (bandgap of GaAs is 1.424 eV).

Since the energies in a bulk active layer are not split up in discrete levels, the individual peaks are most likely the result from longitudinal modes becoming domi-
Figure 4.12: Spectrum at $I=200$ mA, bulk laser $L=100$ $\mu$m, $W=10$ $\mu$m

nant as injection levels increase. Unwanted reflections from nearby lasers will dis­
tort this longitudinal mode spectrum. The reason for this is that light coupled back
into the laser due to unwanted reflections cause interference inside the cavity. At
certain wavelengths this interference is constructive, causing the peak to enhance.
At other wavelengths the interference is destructive, causing those wavelengths not
to appear in the spectrum.
We have not measured the near and far field patterns, as these patterns are distorted
by reflections coming from the bottom of the etch groove.
4.5 Characterisation of the LD-set

4.5.1 DC-characterisation

We have chosen to characterize the LD-set in continuous wave mode (CW) to avoid crosstalk problems experienced with pulse mode operation of the laser. The following characteristics have been recorded: \( P_L = f(I_L) \) and \( I_D = f(P_L) \), in which \( I_L \) is the laser current, \( P_L \) the laser optical output power and \( I_D \) the detector photocurrent.

The laser is connected via an ampere meter to a DC power supply. The detector photocurrent is measured with an ampere meter. No bias is applied to the detector (solar cell mode). The laser output has been measured with an optical power meter. So far, only bulk material lasers with length 300 \( \mu \text{m} \) and width 10 \( \mu \text{m} \) integrated with detectors with length 800 \( \mu \text{m} \) or 1600 \( \mu \text{m} \) and width 20 \( \mu \text{m} \) have been characterised. The LI-curve of the laser operated in CW-mode is given in fig. 4.13 (solid line). The threshold current is 41 \( \text{mA} \) and \( dP/dI = 0.032 \text{ mW/mA} \).

In this graph also the LI-curve as measured with the integrated detector has been drawn (dashed line). As can be seen a detector current of 20 \( \mu \text{A} \) at an output power of 1.6 mW has been obtained. The resulting efficiency of the detector equals approximately 12.5 \( \mu \text{A/mW} \).

The best \( I_D = f(P_L) \) characteristic is shown in fig. 4.14.

As we can see the relationship between detector current and laser output is fairly straight. The slope, however, is becoming less with increasing laser output. During measurement, it has been observed that with constant laser output the detector current show a slow decrementation. We think this is due to optical degradation effects of the uncoated detector facet. The coupling of light into the detector then becomes less efficient, resulting in a lower photocurrent. The sensitivity of the detector, defined as the slope of the \( I_D = f(P_L) \) curve, equals approximately 12.5 \( \mu \text{A/mW} \).

An even better proof of the well functioning of the LD-set is the case when a good detector is integrated with a poor laser, as can be seen in fig. 4.15. The laser has a ridge of 300 \( \mu \text{m} \) long and 10 \( \mu \text{m} \) wide, the detector has a ridge of 1600 \( \mu \text{m} \) long and 20 \( \mu \text{m} \) wide. The laser LI-curve (solid curve) looks bad but is well recorded by the integrated detector (dashed curve). The sensitivity of the detector is about 10 \( \mu \text{A/mW} \). We therefore conclude that the sensitivity of a 1600 \( \mu \text{m} \) long detector is not greater than the one for an 800 \( \mu \text{m} \) long detector. We have not characterised the lasers integrated with the shorter detectors.

Similar results have also been obtained by N. Bouadma, et al. in [12], who have made GaAs/AlGaAs LD-sets with ion beam etched facets. The sensitivity of their detectors was about 5 \( \mu \text{A/mW} \). The LI-curves measured under pulse conditions \((t=1 \mu \text{s}, f=10 \text{ kHz})\) are given in fig. B.15. Threshold currents are 38 mA for the laser with 10 \( \mu \text{m} \) wide ridges and
Bulk laser + detector
Laser: $W=10 \ \mu m$, Detector: $L=800 \ \mu m$

Figure 4.13: LI-curve as measured with the reference detector and the integrated detector (length 800 $\mu m$)
84 mA for lasers with 6 μm wide ridges. Also \( dP/dI = 0.107 \text{ mW/mA} \) for the devices with 10 μm wide ridges and \( dP/dI = 0.091 \text{ mW/mA} \) for the devices with 6 μm wide ridges. The devices with 10 μm wide ridges behave even better than the non-integrated WCEMLs. Behaviour of devices with 6 μm wide ridges is slightly less than the behaviour of corresponding non-integrated WCEMLs. We have also tried to integrate a three quantumwell laser with a photodetector using the same manufacturing process. The lasers with 10 μm wide ridges had a threshold current of 30 mA and a \( dP/dI \) of 0.094 mW/mA. These number are better than those corresponding to WCEMLs not integrated with the detector. However, no reasonable photo-current could be measured. Since the detector has also three quantumwells in its active layer the amount of generated electron-hole pairs is much less than in a bulk active layer.
**Bulk laser and detector**

*Laser: W=10 μm, detector L=1600 μm*

---

**Figure 4.15:** LI-curve as measured with the reference detector and the integrated detector (length 1600 μm)
4.5.2 Spectra

The spectra have been recorded under pulsed conditions \((t=1 \, \mu s, \, f=10 \, kHz)\). Fig. 4.16 shows the spectrum at \(I_L=200 \, mA\) of a laser with a ridge width of 10 \(\mu m\).

![Figure 4.16: Spectrum at \(I_L=200 \, mA\), bulk laser \(L=300 \, \mu m\), \(W=10 \, \mu m\)](image)

Fig. 4.17 shows the spectrum at \(I_L=200 \, mA\) of a laser with a ridge width of 6 \(\mu m\).

![Figure 4.17: Spectrum at \(I_L=200 \, mA\), bulk laser \(L=300 \, \mu m\), \(W=6 \, \mu m\)](image)

The spectra show some broadening with increasing current. However, the peaks are not wider than those of corresponding WCEMLs not integrated with a detector (see the figs 4.10 and 4.11 on page 40. This suggests that the laser does not suffer from unwanted reflections by the detector facet [12], also because no other dominant peaks have been seen.

Concluding we state that the WCEML is an integrable device, and that integrating it with a photodetector can be done without affecting the laser performance for a great deal.
Chapter 5

Conclusions and recommendations

5.1 Conclusions

5.1.1 WCEML

From the experiments carried out the following conclusions can be drawn.

1. The manufacturing process presented in chapter 3 is suitable for the manufacturing process of WCEMLs with multiple quantumwell active layers as well as bulk active layers. The only problem remains the manufacturing of lasers with a ridge width of 4 μm. Wet etching of the mirrors is a reliable process, except that with short devices mirror quality could be affected if the sample is with the epitaxial layers downwards during etching. Therefore this step has to be carried out without stirring and the sample in a horizontal position with the epitaxial layers upwards.

2. For pulse mode characterisation it is not neccesary to mount the devices on a DIL (dual in line) package. These unmounted devices cannot be characterised in continuous wave mode, since heat generated in the devices cannot be transferred effectively away from the devices.

3. Threshold currents of devices processed from multiple quantumwell structures are lower than those of devices with a bulk active layer. The differential efficiencies are generally higher for lasers with bulk active layers than those of multiple quantumwell lasers. The measured data have shown considerable scattering.

4. The spectra of short multiple quantumwell lasers show two or even more peaks with considerable distance to each other. This can be explained from the behaviour of energy levels in quantumwells. Lasers with a bulk active
layer do not show this behaviour, since the energies in the active layer are not split up in discrete levels. Different longitudinal modes in the lasers may become dominant due to (unwanted) reflections from nearby surfaces, resulting in two peaks closely positioned.

5.1.2 WCEML integrated with detector

The following conclusions concerning the WCEML integrated with the detector can be drawn.

1. Integration of the laser with the detector can be done. The tilted detector facet can be obtained by wet chemical etching.

2. The detector photocurrent is almost proportional to the laser optical output.

3. The laser performance is not deteriorated by the presence of the detector. The spectral peak of the laser shows no broadening indicating that the tilt in the detector facet is enough to prevent light reflected by this facet to be coupled into the laser.

4. The detector photocurrent drops when keeping the laser output constant. This is probably due to optical damage induced in the detector facet.

5.2 Recommendations

5.2.1 WCEML

The following recommendations are done.

1. To improve the quality of the mirrors of short devices, wet etching of these mirrors should be carried out with the epitaxial layer upwards.

2. Resist processes for lift-off should be performed carefully. If a change in development time or if the lift-off becomes difficult the process should be optimised. Resist profiles are best watched in a scanning electron microscope (SEM).

3. Devices with one or four quantumwells in the active layer should be fabricated and characterised.

4. The processing of a laser with dry etched mirrors can be investigated. Etching of the mirrors using dry etch methods rather than wet chemical etching introduces problems of its own. It is beyond the scope to discuss these problems in full detail.
5.2.2 WCEML integrated with detector

For the integrated laser and detector we recommend the following.

1. To prevent optical damage of the detector facet (and the laser mirrors) this facet should be coated or intermixed. Intermixing involves the process of annealing a GaAs or AlGaAs wafer with a layer of PECVD deposited silicon oxide (SiO$_2$) at high temperatures (900°C). The result is that gallium atoms from the semiconductor diffuse in the SiO$_2$ layer. Experiments show that the bandgap energy of the semiconductor is enlarged. This way, intermixed laser mirrors or detector facets become transparent for the light emitted from the laser. This can contribute to a reduction of COD.

2. The DC characteristics of the laser and detector should be measured with reverse bias applied to the detector.

3. The dynamic behaviour of the laser and detector should be measured. To improve dynamic behaviour of the devices, silicon oxide deposited by PECVD should be used instead of silicon nitride. Silicon oxide has a lower dielectric constant and thus result in lower parasitic capacitances.

4. Further integration of lasers with other devices should be investigated. The integration of a laser with a transistor has been reported by Bouadma et al in [12].
5.3 Acknowledgements

The devices presented in this thesis have been fabricated with the support of many people within and outside the TUE Electronic Devices Community. I would like to thank all of them, especially the following persons, who deserve full credit for their contribution in the project.

- My parents and family for making me possible and giving mental support during this project.

- Barry Smalbrugge for polishing, mounting and bonding the devices and giving some very useful hints.

- Erik Jan Geluk for doing all metal evaporation and making the SEM-pictures.

- Judith van Praagh for teaching me most processing steps.

- Frans Lenting for writing the PC software to read in the measurement data.

Finally I would like to thank Fouad Karouta, for working out the idea of the wet chemically etched mirror laser and the WCEML integrated with the monitoring detector, prof. Acket for reviewing this report and for fruitful discussion and prof. Kaufmann for giving me the opportunity to do this great job.

Herman Langeler
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Appendix A

process overview laser+detector

Cleaving
- Cleaving of the wafer
- Particle removal with $N_2$ blow

Orientation !!

Removing native oxide
- Rinsing in ammonium solution: DI-water = 1:10, 1 min
- Rinsing in DI-water
- $N_2$ blow dry
Ridges and passivation layer

Cleaning
- Rinsing in acetone, 2 min
- Rinsing in isopropanol, 2 min
- N₂ blow dry
- Bake 5 min 105°C

Resist
- AZ5214, 5000 rpm, 30 s
- Soft bake 5 min 95°C

Exposure
- Flood exposure 2.6 s, UV300
- Bake 5 min 105°C
- Mask 1: mesa
- Mask exposure 31 s, UV300
- Development (1:1), 1 min 25 s
- Rinsing in DI-water
- N₂ blow dry

- Hard bake 10 min 105°C

Wet etching
- H₃PO₄ : H₂O₂ : CH₃OH = 20:20:60 at 0°C
  Etch rate 0.35 μm/min, sample upside down
  Required mesa height=1.8 μm
- Rinsing firmly in DI-water
- Rinsing in DI-water
- N₂ blow dry

Visual check

Check mesa height

Deposition passivation layer (SiNx)
- Clustertool recipe SiNx-dep-100
- Deposition rate 50 nm /min, deposition time 5 min

Lift off
- Ultrasonic vibration in acetone, 2 min
- Rinsing in acetone, 1 min
- Rinsing in isopropanol, 1 min
- N₂ blow dry

Visual check

Measure resist height
P-contact

Baking passivation layer
- RTA recipe 450A-M10.1

Cleaning
- Rinsing in acetone, 2 min
- Rinsing in isopropanol, 2 min
- \( \text{N}_2 \) blow dry
- Bake 5 min 105\(^{\circ}\)C

Resist
- AZ5214, 5000 rpm, 30 s
- Soft bake 5 min 95\(^{\circ}\)C

Exposure
- Flood exposure 2.6 s, UV300
- Bake 5 min 105\(^{\circ}\)C
- Mask 2: p-metal
- Mask exposure 31 s, UV300
- Development (1:1), 1 min 25 s
- Rinsing in DI-water
- \( \text{N}_2 \) blow dry

Evaporation of the p-contact
- Leybold
- Ti/ Pt/ Au (50/20/200 nm)

Lift off
- Acetone spray bottle (or boiling acetone or ultrasonic vibration)
- Rinsing in acetone, 1 min
- Rinsing in isopropanol, 1 min
- \( \text{N}_2 \) blow dry

Visual check
Etch windows in passivation layer for mirrors

Cleaning
- Rinsing in acetone, 2 min
- Rinsing in isopropanol, 2 min
- N₂ blow dry
- Bake 5 min 105°C

Resist
- AZ5214, 5000 rpm, 30 s
- Soft bake 5 min 95°C

Exposure
- Mask 3: silox
- Mask exposure 5 s, UV400
- Development (1:1), 30 s
- Rinsing in DI-water
- N₂ blow dry

Dry etch SiNx
- Clustertool recipe SiNx-etch
- Etch rate 70 nm/min, etch time 4 min 30 s

Resist removal
- Acetone spray bottle
- Rinsing in acetone, 1 min
- Rinsing in isopropanol, 1 min
- N₂ blow dry

- If still resist left use O₂ plasma, 5 min
  (Clustertool recipe O2-etch-ST1)

Visual check

Visual check

Visual check
Etch detector facet

This step is omitted when processing WCEMLs

Cleaning
- Rinsing in acetone, 2 min
- Rinsing in isopropanol, 2 min
- N₂ blow dry
- Bake 5 min 105°C

Resist
- AZ5214, 5000 rpm, 30 s
- Soft bake 5 min 95°C

Exposure
- Mask 5: detect
- Mask exposure 5 s, UV400
- Development (1:1), 30 s
- Rinsing in DI-water
- N₂ blow dry

Visual check
- Hard bake 10 min 105°C

Wet etching
- H₂SO₄ : H₂O₂ : H₂O = 10:10:100 at 20°C
  sample upside down, etch rate 0.75 μm/min
  etch time 2 min 30 s
- Rinsing firmly in DI-water
- Rinsing in DI-water
- N₂ blow dry

Resist removal
- Acetone spray bottle
- Rinsing in acetone, 1 min
- Rinsing in isopropanol, 1 min
- N₂ blow dry

Check etch depth
Etch laser mirrors

Cleaning
- Rinsing in acetone, 2 min
- Rinsing in isopropanol, 2 min
- N\textsubscript{2} blow dry
- Bake 5 min 105\degree C

Resist
- AZ5214, 5000 rpm, 30 s
- Soft bake 5 min 95\degree C

Exposure
- Mask 4: mirror
- Mask exposure 5 s, UV400
- Development (1:1), 30 s
- Rinsing in DI-water
- N\textsubscript{2} blow dry

Wet etching
- H\textsubscript{3}PO\textsubscript{4} : H\textsubscript{2}O\textsubscript{2} : CH\textsubscript{3}OH = 30:30:30 at 20\degree C
  sample upside down, etch rate 3.6 \mu m/min
  etch time 1 min 25 s
- Rinsing firmly in DI-water
- Rinsing in DI-water
- N\textsubscript{2} blow dry

Resist removal
- Acetone spray bottle
- Rinsing in acetone, 1 min
- Rinsing in isopropanol, 1 min
- N\textsubscript{2} blow dry

Alloying p-contact
- RTA recipe 400A-M01.1
Polishing, n-contact and cleaving

Polishing
- Required thickness 130 μm

Evaporation of the n-contact
- Should be done directly after the last polishing step
- Ge/ Ni/ Au (20/15/200 nm)
- In Leybold

Alloying n-contact
- RTA recipe 400A-M01.1

Cleaving
- AZ1505, 5000 rpm, 30 s
- Soft bake 1 min 95°C

Remarks
- Processing temperature is room temperature (20°C), unless otherwise stated
- Bakes are performed on hot plates in normal processing ambient.
- Rinsing in DI-water until resistance of the water exceeds 5 MΩ.
- Resist recipes are valid at a lamp power of 12 mW/cm² (measured with UV400 filter) At other lamp power exposure times and/or development times may be different!!
- Development (1:1) means rinsing in a solution containing 60 ml AZ-developer and 60 ml DI-water.
- If SiO₂ is used as the passivation layer, HMDS primer (5000 rpm, 30 s) should be used prior to resist spinning in all steps following the deposition (i.e. p-contact and further). Deposition time of SiO₂ is 8 minutes (recipe SiO2-dep-100).
- All depositions are done at T=100°C. Cooling down chamber 3 of the cluster tool from 300°C to 100°C takes 24 hours!!!
- Etch rates of wet etchants should be determined using a GaAs dummy. Processing for this dummy consists of step 1 (mesa) without deposition, step 4 (detector facet) and step 5 (laser mirrors).
- All steps printed on one page should be performed in one day (except the polishing).
Clustertool recipes used in the process

**Chamber 3**

**SiNx-dep-100**

Top manifold

- \(N_2 = 100.0 \text{ sccm}\)
- \(NH_3 = 21.0 \text{ sccm}\)

Bottom manifold

- \(SiH_4 = 3.0 \text{ sccm}\)
- \(N_2 = 50.0 \text{ sccm}\)

\(T=100^\circ C, MW \text{ power}=250 \text{ W}, p=200 \text{ mtorr}\)

Deposition rate 50 nm/min

**SiOx-dep-100**

Top manifold

- \(N_2O = 30.0 \text{ sccm}\)
- \(N_2 = 60.0 \text{ sccm}\)

Bottom manifold

- \(SiH_4 = 3.0 \text{ sccm}\)
- \(N_2 = 40.0 \text{ sccm}\)

\(T=100^\circ C, MW \text{ power}=250 \text{ W}, p=200 \text{ mtorr}\)

Deposition rate 30 nm/min

**Chamber 1**

**SiNx-etch**

- \(SF_6 = 10.0 \text{ sccm}\)
- \(Ar = 2.0 \text{ sccm}\)

\(MW \text{ power}=400 \text{ W}, RF \text{ power}= 20 \text{ W}\)

Etch rate 70 nm/min

**SiOx-etch**

- \(SF_6 = 10.0 \text{ sccm}\)
- \(Ar = 2.0 \text{ sccm}\)

\(MW \text{ power}=400 \text{ W}, RF \text{ power}= 15 \text{ W}\)

Etch rate -

**O2-etch-ST1**

- \(O_2 = 30.0 \text{ sccm}\)
- \(MW \text{ power}=400 \text{ W}, RF \text{ power}= 50 \text{ W}\)
Appendix B

graphics
Figure B.1:
Figure B.2:
Figure B.3:

2QW WCEML
Threshold current

![Threshold current graph]

Figure B.4:

2QW WCEML
Threshold current density

![Threshold current density graph]
Figure B.5:
Figure B.6:
3QW WCEML
Threshold current

Figure B.7:

3QW WCEML
Threshold current density

Figure B.8:
3QW WCEML
Differential efficiency

Figure B.9:
Figure B.10:
Figure B.11:
Figure B.12:

Bulk WCEML
Threshold current density

Figure B.13:
Figure B.14:
Integrated bulk WCEML
L = 300 μm

W = 10 μm

W = 6 μm

Figure B.15:
# Appendix C

## Used equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Manufacturer/Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster tool</td>
<td>Oxford Plasmalab Systems</td>
</tr>
<tr>
<td>E-beam evaporation system</td>
<td>Leybold LH560UV</td>
</tr>
<tr>
<td>Rapid Therma Annealer</td>
<td>AST SHS100</td>
</tr>
<tr>
<td>Scanning Electron Microscope</td>
<td>JEOL 6400-F</td>
</tr>
<tr>
<td>Profiler</td>
<td>Tencor Alphastep 2000</td>
</tr>
<tr>
<td>Oscilloscope</td>
<td>Hewlett Packard 54602B</td>
</tr>
<tr>
<td>Pulse source</td>
<td>Hewlett Packard 214B</td>
</tr>
<tr>
<td>Multimeter</td>
<td>Fluke 8000A</td>
</tr>
<tr>
<td>Multimeter</td>
<td>Keithley 2000</td>
</tr>
<tr>
<td>Spectrum analyser</td>
<td>ANDO AQ-6310B</td>
</tr>
<tr>
<td>Optical power meter</td>
<td>Newport model 1835-C</td>
</tr>
</tbody>
</table>

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